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Physiological responses associated with improved yield performance under heat stress in proso millet: the role of rice bran-coated urea in re-programming growth and partitioning

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Abstract

Objective: Heat stress disrupts the photosynthetic machinery and shortens developmental phases, leading to yield loss in cereals. This study investigated the potential of rice bran-coated urea (RBCU) to ameliorate heat-induced constraints on growth, phenology, and dry matter partitioning in proso millet (*Panicum miliaceum* L.).

Methods: A two-year field experiment evaluated uncoated urea (UCU), RBCU, gypsum-coated urea (GCU), and cement-coated urea (CCU) at four nitrogen rates (0, 60, 80, and 120 kg urea ha^{-1}) under optimal (spring) and heat stress (summer) conditions. The experiment was conducted as a split-plot factorial arrangment based on a randomized complete block design with three replications. The main plots included planting season (spring and summer seasons), while the subplots consisted of the factorial combination of coating type and urea-N rate. In this study, several traits, including days to heading, days to physiological maturity, chlorophyll a, total carotenoids, leaf area, panicle length, biomass, grain yield, and harvest index, were measured.

Results: The results indicated that RBCU at 80 kg urea ha^{-1} generally ranked among the best-performing treatments, particularly under summer conditions. Under summer heat stress, RBCU maintained significantly higher chlorophyll a and carotenoid contents, increasing chlorophyll *a* and carotenoids by 25.4% and nearly twofold, respectively, compared with the stressed UCU control. It concurrently improved canopy architecture, increasing leaf area and panicle length by 14.9% and 15.2%, respectively. RBCU also modulated crop phenology by delaying heading by 11.5%, and was associated with an improved dry matter partitioning efficiency, reflected in a higher harvest index. It increased total biomass by 17.3% and, most importantly, enhanced the harvest index by 6.3% under severe stress, indicating a more efficient allocation of assimilates to grains. Consequently, grain yield with RBCU at 80 kg urea ha^{-1} was 17.5% higher than that with UCU under summer conditions.

Conclusion: RBCU was associated with improved physiological performance and higher yield under summer heat conditions, likely through coordinated effects on canopy traits, phenology, and harvest index.

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Introduction

Proso millet (*Panicum miliaceum* L.) is valued for its short life cycle and drought tolerance, making it a strategic crop for semi-arid and heat-prone regions. However, its cultivation increasingly overlaps with periods of intense heat stress, a major limitation to cereal production that severely constrains productivity (Wahid *et al.* 2007; Reynolds *et al.* 2010**).** High temperatures accelerate developmental rates, truncate the grain-filling period, and impair photosynthetic function (Wahid *et al.* 2007; Fahad *et al.* 2017). This leads to reduced source (assimilate production) capacity and can directly damage reproductive structures, impairing sink (grain) strength and creating a critical mismatch between source supply and sink demand (Farooq *et al.* 2009). Consequently, yield reduction under heat stress is often associated with accelerated phenology, reduced leaf area duration, and impaired source–sink relationships rather than direct cellular damage alone (Reynolds *et al.* 2010).

Plant adaptation to such stress involves complex physiological trade-offs. Maintaining an efficient photosynthetic canopy (source) through preserved leaf area and chlorophyll content is essential for continuous assimilate supply (Ashraf and Harris 2013), a trait commonly used for screening stress-tolerant genotypes (Mohammadi and Sorkhi 2017). Equally critical is the temporal alignment of developmental phases (phenology) with favorable environmental conditions; even minor shifts in flowering time can affect yield under terminal heat stress (Bheemanahalli *et al.* 2019). Ultimately, crop yield is a function of total biomass accumulation and the proportion of that biomass partitioned to the harvestable grains, quantified as the harvest index (HI). Consequently, identification of morpho-physiological traits that contribute to yield stability under high temperatures has become a central objective in physiological breeding programs (Blum 2011). A resilient genotype or management practice under stress often maintains or improves HI by protecting both source and sink activities and their functional coordination (Araus *et al.* 2008).

In cereals such as wheat, nitrogen management has been shown to significantly influence the remobilization of stem reserves and harvest index under terminal stress (Ghahramani *et al.* 2018; Seied-Khamesi *et al.* 2022), highlighting the critical role of nutrient timing in dry matter partitioning.

More specifically, nitrogen supply is a key modulator of a plant's ability to cope with drought, influencing a suite of physiological responses that determine final yield (Choukan *et al*. 2016; Cossani and Sadras 2018). Nitrogen management is therefore pivotal for all these processes, as improving nitrogen use efficiency remains a cornerstone of cereal productivity (Raun and Johnson 1999)**.** Nitrogen is a core component of chlorophyll, Rubisco, and other photosynthetic proteins, making it indispensable for source strength. It also influences plant architecture, tillering, and sink development. However, conventional urea fertilization is inefficient, as rapid nitrogen losses lead to asynchronous nutrient supply (Fageria and Baligar 2005). Conventional urea fertilizers frequently fail to meet crop nitrogen demand under heat stress because of rapid nitrogen release and increased losses. This mismatch can exacerbate stress by causing initial toxicity or subsequent deficiency during critical reproductive stages, ultimately undermining the physiological processes that confer resilience (Chen *et al*. 2020). In contrast, controlled-release nitrogen fertilizers can prolong nitrogen availability, thereby supporting sustained canopy development, delayed senescence, and improved biomass partitioning under adverse environmental conditions (Trenkel 2010). Controlled-release fertilizers, including bio-based and organic-coated formulations, have been reported to improve nitrogen use efficiency and stress tolerance in cereals (Shaviv and Mikkelsen 1993; Ahmad *et al*. 2022). Studies in maize have demonstrated that controlled-release urea can significantly enhance dry matter accumulation, nitrogen uptake, and nitrogen use efficiency (Guo *et al.* 2020), as well as improve overall stress resilience through enhanced soil-plant interactions (Chen *et al.* 2020).

Despite these advances, information on the physiological basis of yield stability in proso millet under combined heat stress and nitrogen management strategies remains limited. While studies on other crops, such as quinoa, have demonstrated that nitrogen levels can modulate physiological and yield responses to drought (VaziriMehr *et al.* 2024), and despite the acknowledged role of nitrogen in fine-tuning crop growth under combined stresses (Cossani and Sadras 2018), the specific influence of synchronized nitrogen release through organic, biodegradable coatings such as rice bran on the integrated physiological sequence governing yield under heat stress in millets-from photosynthetic competence and canopy development, through phenological adjustment, to final biomass partitioning-remains largely unexplored.

The objective of this study was to evaluate the effects of rice-bran coated urea (RBCU) and nitrogen rate on phenological traits, canopy development, biomass production, and grain yield of proso millet under contrasting planting seasons.

Materials and Methods

Plant material, growth conditions, and experimental site

A two-year field experiment was conducted during the 2024 and 2025 growing seasons in Al-Muthanna Governorate, Iraq (31.5° N, 45.3° E; 120 m altitude). The region features a semi-arid climate (Köppen: BSh). To create contrasting thermal regimes, proso millet (cv. Mahoor) was sown in mid-March (optimal spring season, mean maximum temperature: 32.7 ± 2.5 °C) and mid-June (heat stress summer season, mean maximum temperature: 42.5 ± 3.1 °C). The soil was sandy loam with low organic carbon content (0.45%) and an alkaline pH (8.2).

Experimental design and treatments

The experiment was arranged as a split-plot factorial design based on a randomized complete block design with three replications. Planting seasons (Spring vs. Summer) were assigned to the main plots, while the factorial combination of coating type [uncoated urea (UCU, control),), gypsum-coated urea (GCU), cement-coated urea (CCU), and RBCU] and urea-N rate (0, 60, 80, and 120 kg urea ha^{-1}) was arranged to the subplots. All plots received uniform basal applications of phosphorus and potassium fertilizers based on soil-test recommendations. Nitrogen treatments were split-applied at tillering (30 days after sowing, DAS) and stem elongation (55 DAS). Each subplot had an area of 12 m² (3 m × 4 m). Standard agronomic practices were uniformly followed across all treatments to minimize confounding effects.

Preparation of coated urea

Coated urea granules were prepared on-site following a standard coating procedure. Commercial urea prills (46% N) were coated in a rotary drum using a 5% (w/v) Arabic gum solution as an adhesive and finely sieved coating materials (rice bran, gypsum, and cement). The coated granules were dried at 40–50 °C for 12 h to ensure stability. An *in-vitro* dissolution test in distilled water confirmed the slow-release properties of the coated fertilizers: more than 80% of N from coated urea was released over 28 days, compared with more than 95% from uncoated urea within 7 days.

Measurements of traits

Photosynthetic pigments: Chlorophyll a and total carotenoids were extracted from fresh leaf samples collected at flowering (70 DAS) using 80% acetone and quantified using a spectrophotometer according to Lichtenthaler (1987).

Phenological stages: The number of days from sowing to 50% heading (days to heading) and physiological maturity (days to maturity) were recorded for each plot.

Canopy traits: At physiological maturity, panicle length (cm) was measured in 10 randomly selected plants from the central rows of each plot. Leaf area (cm^2 $plant^{-1}$) was measured at the flowering stage on the youngest fully expanded leaf using a portable leaf area meter.

Biomass, yield, and harvest index: At harvest, plants from a defined area (2 m^2) were harvested to determine biomass (t ha^{-1}) after oven-drying at 70 °C to constant weight. Grain yield (t ha^{-1}) was determined after threshing and adjusting to 12% moisture. The HI (%) was calculated as follows:

$$HI = (\text{Grain yield} / \text{Biomass}) \times 100.$$

Statistical analysis

All data were subjected to a four-way analysis of variance (ANOVA) appropriate for a split-plot factorial design using SAS software (version 9.1, SAS Institute Inc., Cary, NC, USA). The significance of sources of variation was tested according to the expected mean squares, considering season, coating, and N rate as fixed factors and replication and year as random factors. The assumptions of normality and homogeneity of variances were verified by the Shapiro-Wilk test and residual plots, respectively. Treatment means were compared using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$.

Results

Phenological traits

The four-way interaction among urea coating type, nitrogen rate, planting season, and year was significant for days to 50% heading; however, for days to physiological maturity, only several two-way interactions, including urea coating type × nitrogen rate, planting season × coating type, nitrogen rate × year, coating type × year, and planting season × year, were significant (Table 1). Nitrogen management significantly influenced phenological development. Application of coated urea, particularly RBCU at 80 and 120 kg urea ha^{-1}, induced a significant delay in key developmental stages. Summer planting accelerated phenological development; however, RBCU significantly delayed heading compared with uncoated urea, particularly at moderate nitrogen rates (Figures 1c and 1d). Under the intense heat of summer 2024, plants treated with RBCU (80 kg urea ha^{-1}) reached 50% heading in 50.23 days, compared with 45.03 days for the UCU control, representing an 11.5% longer vegetative phase (Figure 1c). This delay was also evident under spring conditions, indicating a consistent effect of coating type on delaying heading time. Furthermore, progression to physiological maturity was also extended under RBCU treatment. The RBCU coating resulted in later maturity compared with the control, indicating a potentially longer grain-filling period critical for yield determination under stress (Figure 2).

Table 1. Combined analysis of variance for physiological and yield-related traits of proso millet grown under different urea coatings and nitrogen rates across two years and planting seasons.

Source of variation	**df**	**Mean Squares**								
		DTH	**DTM**	**LA**	**PL**	**BY**	**HI**	**GY**	**Chl a**	**Car**
Y	1	2730.8**	1695.0**	9761.5**	2589.8**	402.5**	4.28**	12.63**	25.13**	32.12**
S	1	3074.4	481.8	14174.1	1055.9*	224.2	124.5	1.63	0.54	10.51
Y × S	1	357.2**	3405.0**	2086.0**	5.72**	55.12**	186.9**	0.031**	1.15**	4.20**
R (Y×S)	8	0.55	0.57	0.45*	0.47*	0.17**	0.26	0.0014	0.0015	0.0023
C	3	44.2	14.5	659.2	45.0	7.23*	55.24	1.17	1.74	1.28
N	3	117.8	28.5*	1269.3*	267.7	27.11*	178.3**	4.89	3.72**	6.02*
Y × C	3	15.0**	2.56**	124.7**	17.06**	0.64**	47.05**	0.68**	0.42**	0.42**
S × C	3	5.60	2.58**	194.7	2.50	0.45	11.34	0.067	1.99	0.14
Y × N	3	50.20**	2.42**	99.17**	90.58**	2.25**	1.14**	0.14**	0.11**	0.64**
S × N	3	2.76	0.36	7.62	5.06	0.05	0.12	0.012	0.25	0.067
C × N	9	6.49	1.23**	56.66*	9.16*	1.09*	3.60	0.086	0.38	0.21
Y × S × C	3	1.56**	0.60	305.6**	1.96**	0.39**	9.91**	0.037**	0.67**	0.30**
Y × S × N	3	1.03*	0.34	273.7**	3.90**	0.42**	10.03**	0.16**	0.17**	0.13**
Y × C × N	9	4.26**	0.54	13.02**	1.82**	0.27**	5.99**	0.090**	0.12**	0.23**
S × C × N	9	0.55	0.13	7.46	1.49	0.28	6.53	0.046	0.11	0.091
Y × S × C × N	9	1.10**	0.23	25.40**	0.93**	0.15**	4.17**	0.031**	0.11**	0.22**
Error	120	0.31	0.30	0.17	0.20	0.053	0.15	0.0052	0.0017	0.0024
Total	191									
CV (%)		1.2	1.4	0.4	1.5	2.7	2.9	5.7	2.0	3.3

Abbreviations: df: Degrees of freedom, Y: Year, S; Season, R: Replication, C: Coating, N: Nitrogen, DTH: Days to 50% heading, DTM: Days to physiological maturity, LA: Leaf area, PL: Panicle length, BY: Biomass, HI: Harvest index, GY: Grain yield, Chl a: Chlorophyll a, Car: Carotenoids, CV: Coefficient of variation; *, **: Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively.

Photosynthetic pigments and canopy architecture

The four-way interaction among year, planting season, urea coating type, and nitrogen rate significantly affected chlorophyll a, carotenoid content, leaf area, and panicle length. Summer heat stress significantly reduced the content of photosynthetic pigments. However, RBCU at 80 kg urea ha^{-1} resulted in significantly higher pigment levels than uncoated urea under summer conditions. In summer 2024, RBCU at 80 kg urea ha^{-1} maintained chlorophyll *a* content at 2.913 mg g^{-1} FW, which was 25.4% higher than that of the UCU control at the same N rate (2.323 mg g^{-1} FW) (Figure 3c). A similar trend was observed for carotenoids, with RBCU recording 2.860 nmol g^{-1} FW, representing nearly a twofold increase compared with UCU (Figure 4c). This preservation of the photosynthetic apparatus was accompanied by a more robust canopy structure. Leaf area and panicle length were significantly reduced under summer planting conditions (Figures 5 and 6). Application of RBCU mitigated these reductions and resulted in higher leaf area and longer panicles compared with the uncoated urea treatments under heat stress in 2024 (Figures 5c and 6c). Under summer stress in 2024, plants treated with RBCU (80 kg urea ha^{-1}) achieved a significantly greater leaf area (112.2 cm^2) than those treated with UCU (97.6 cm^2), representing a 14.9% increase. Likewise, RBCU-treated plants produced longer panicles (35.37 cm) than UCU-treated plants (30.70 cm), representing a 15.2% increase (Figures 5c, 6c).

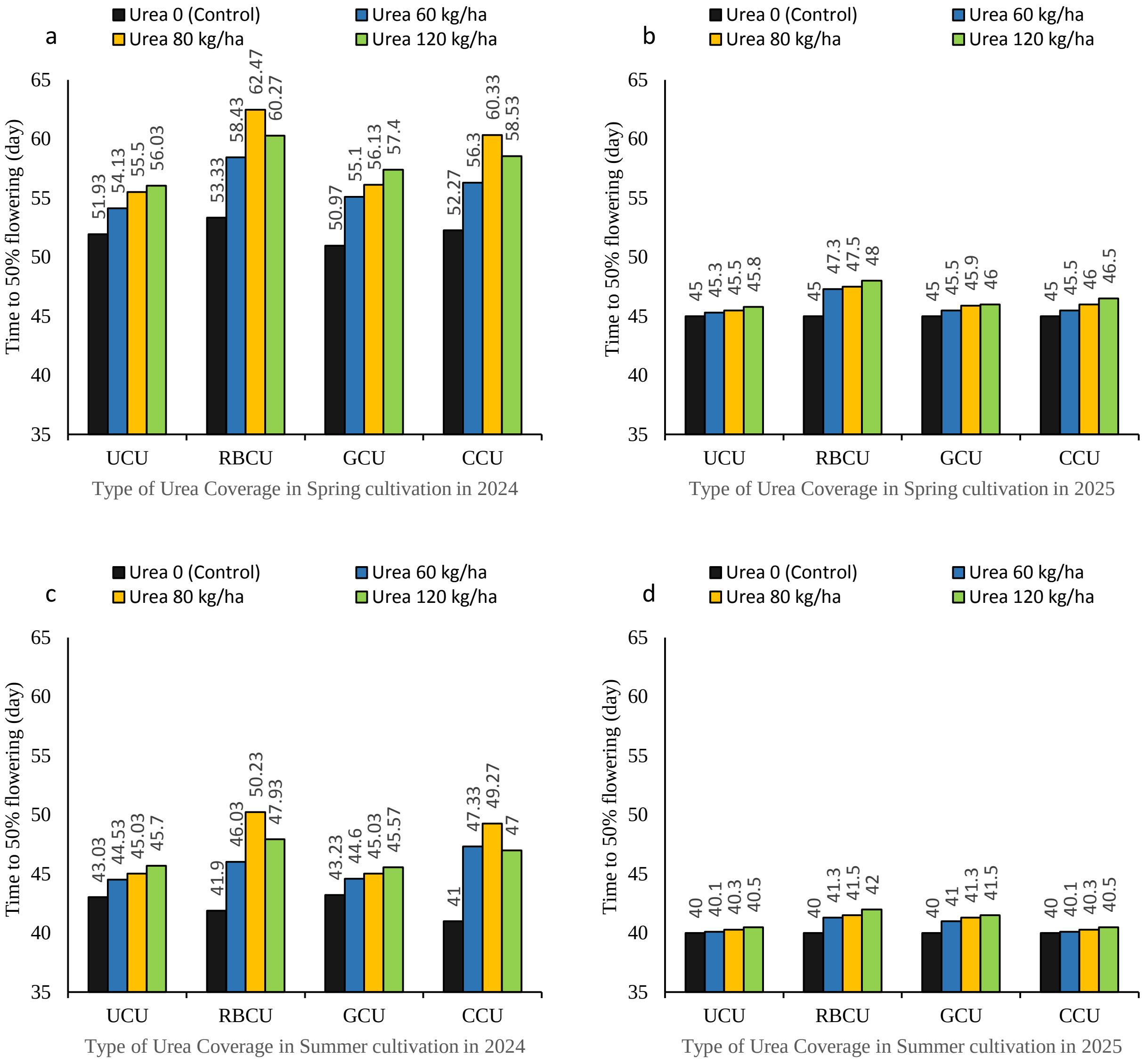

Figure 1. Interactive effects of year, planting season, urea coating type, and nitrogen rate on days to 50% heading in proso millet. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 1.92.

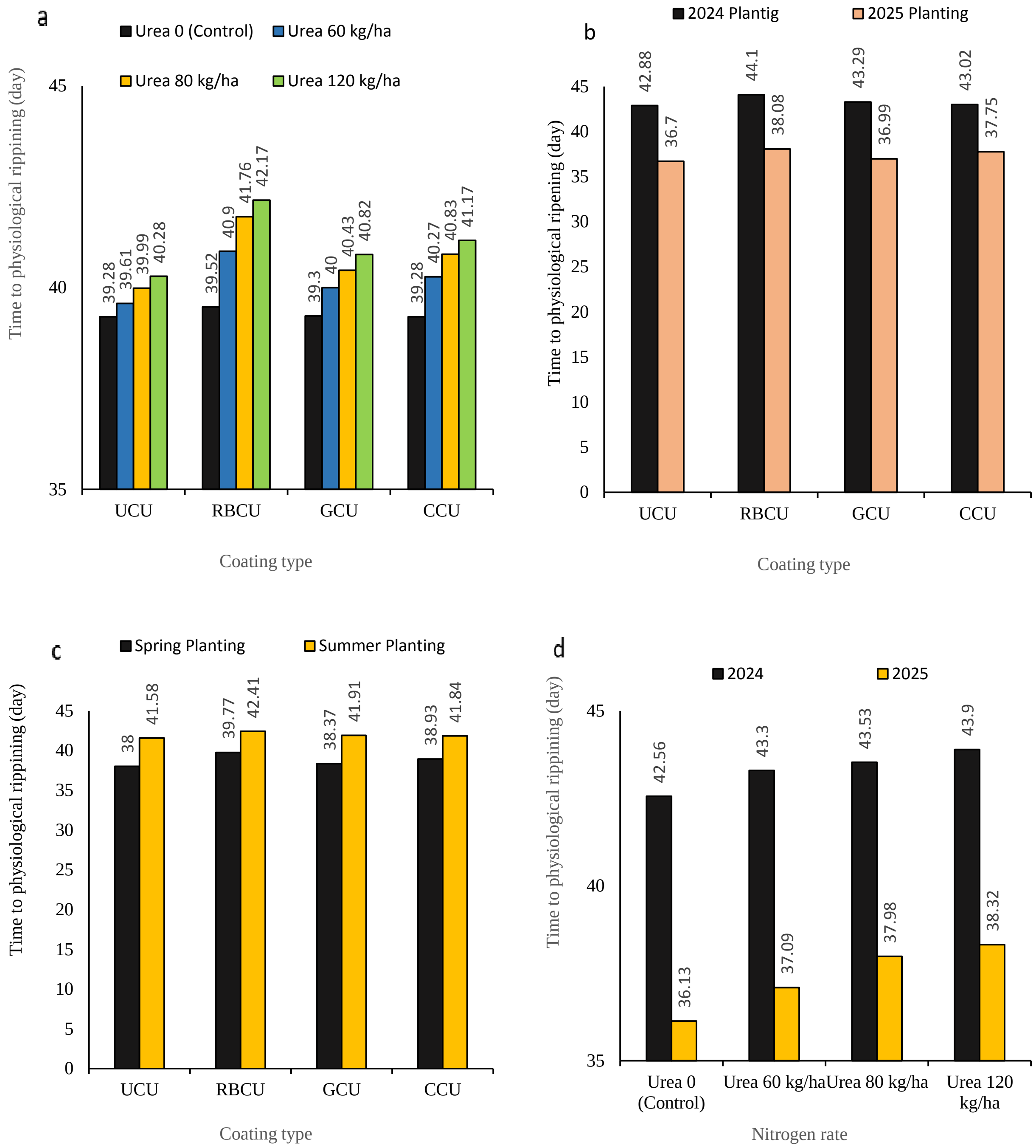

Figure 2. Interactive effects of year, planting season, urea coating type, and nitrogen rate on days to physiological maturity in proso millet. (a): Coating type × Nitrogen rate, (b): Year × Coating type, (c): Planting season × Coating type, (d): Year × Nitrogen rate; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% (Figure 2a) = 0.781, HSD5% (Figure 2b) =0.485, HSD5% (Figure 2c) =0.485, HSD5% (Figure 2d) =0.485.

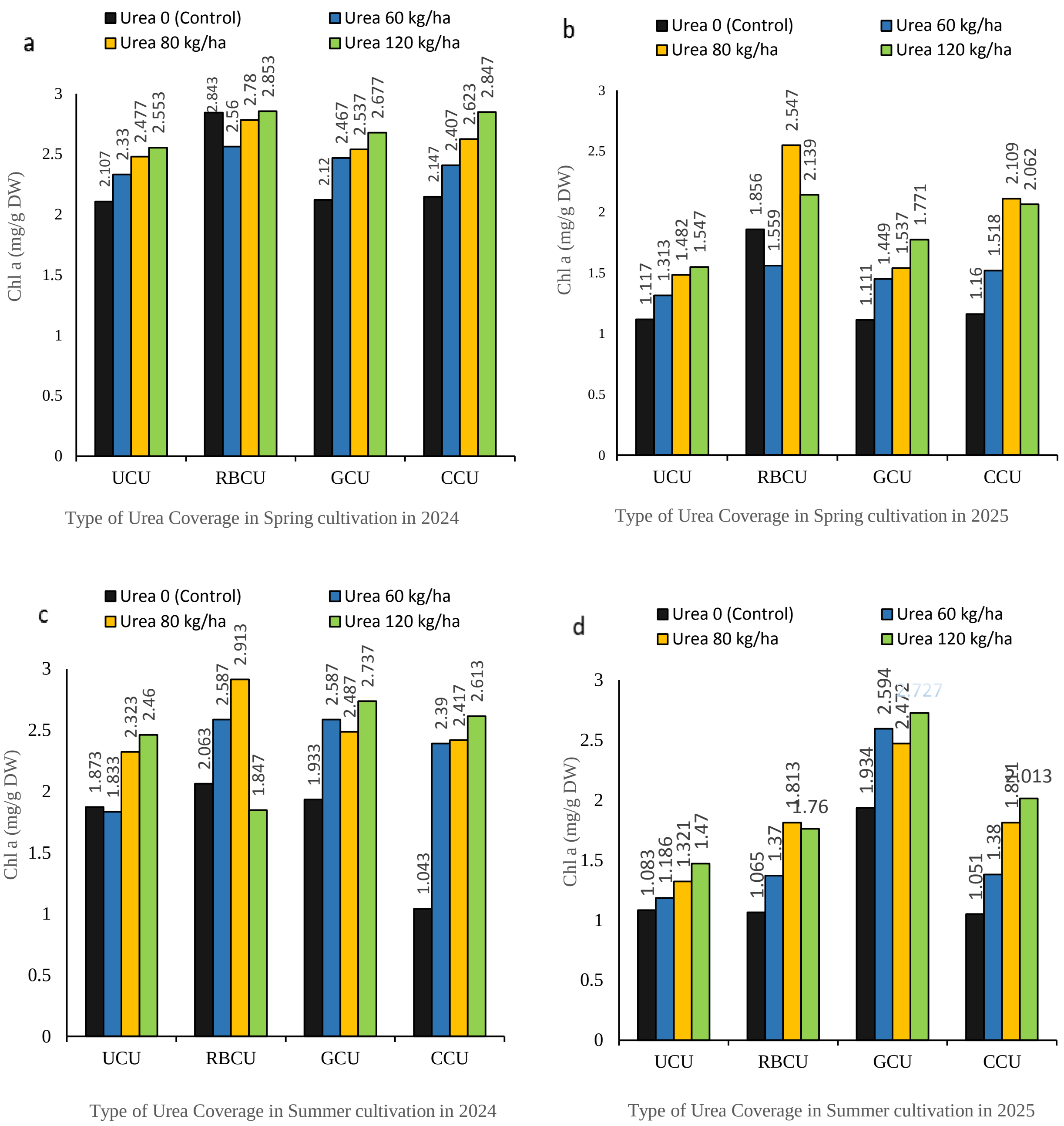

Figure 3. Interactive effects of year, planting season, urea coating type, and nitrogen rate on the chlorophyll *a* content in the proso millet leaves. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 0.142.

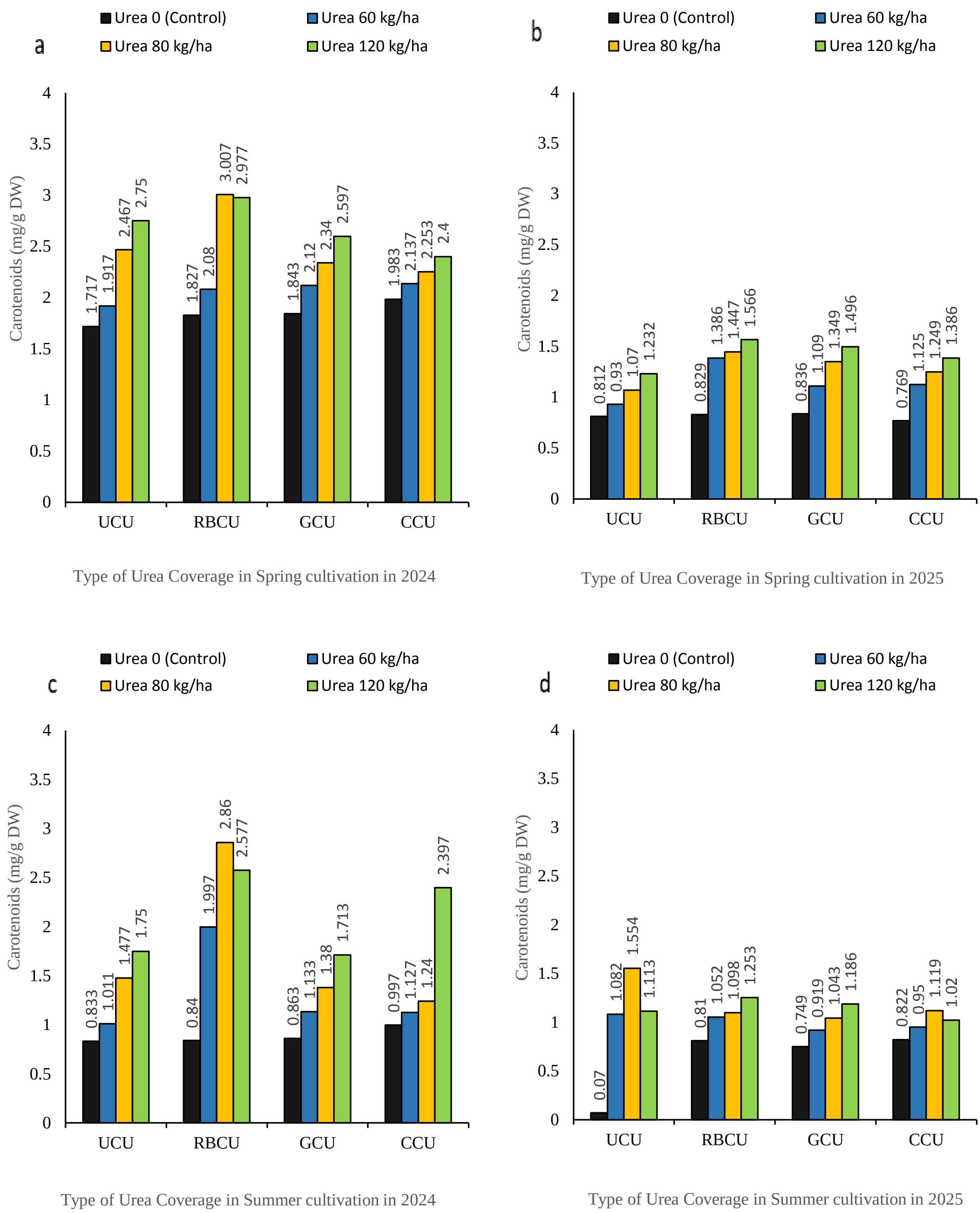

Figure 4. Interactive effects of year, planting season, urea coating type, and nitrogen rate on total carotenoid content in the proso millet leaves. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 0.169.

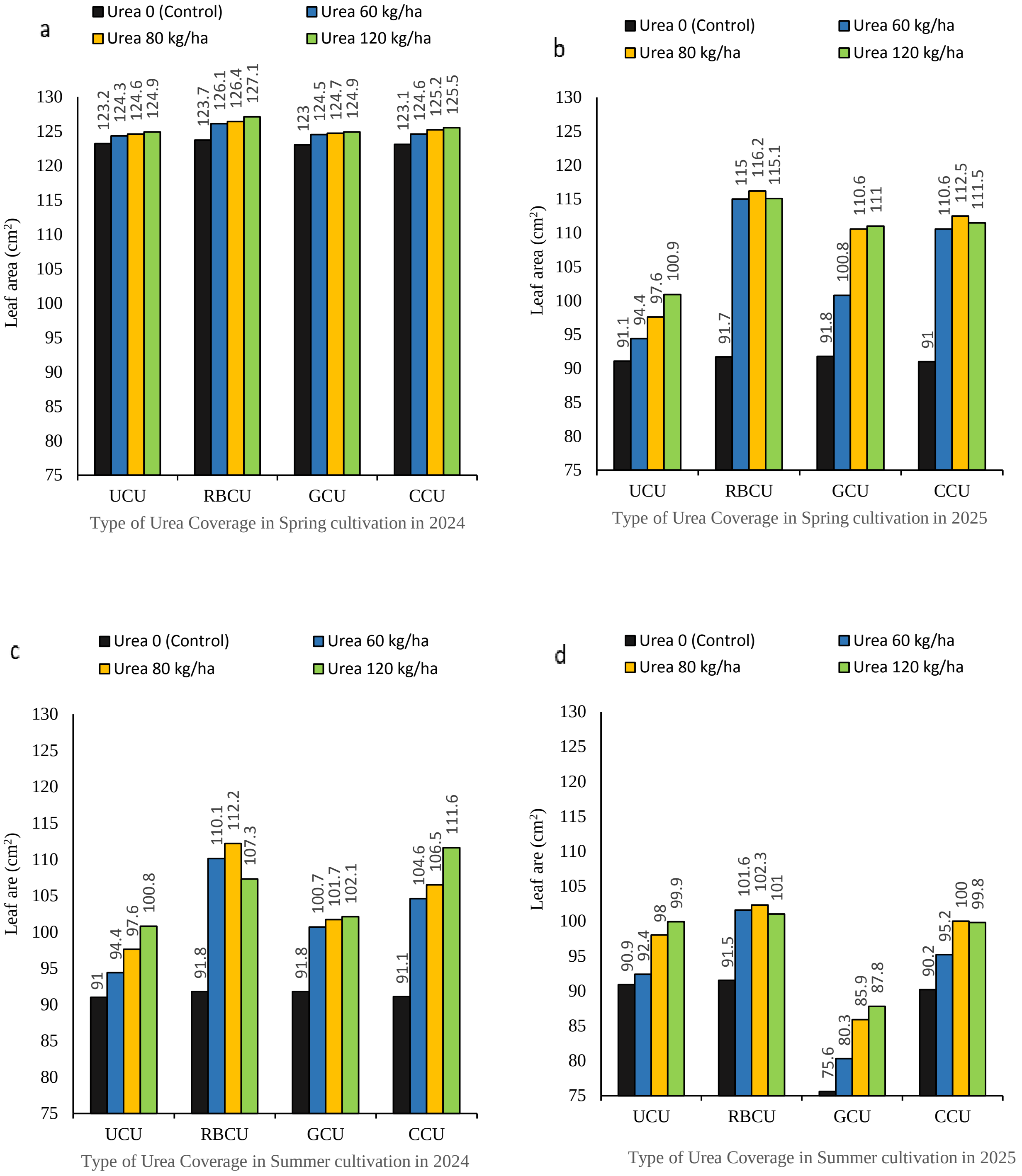

Figure 5. Interactive effects of year, planting season, urea coating type, and nitrogen rate on leaf area in proso millet. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 1.421.

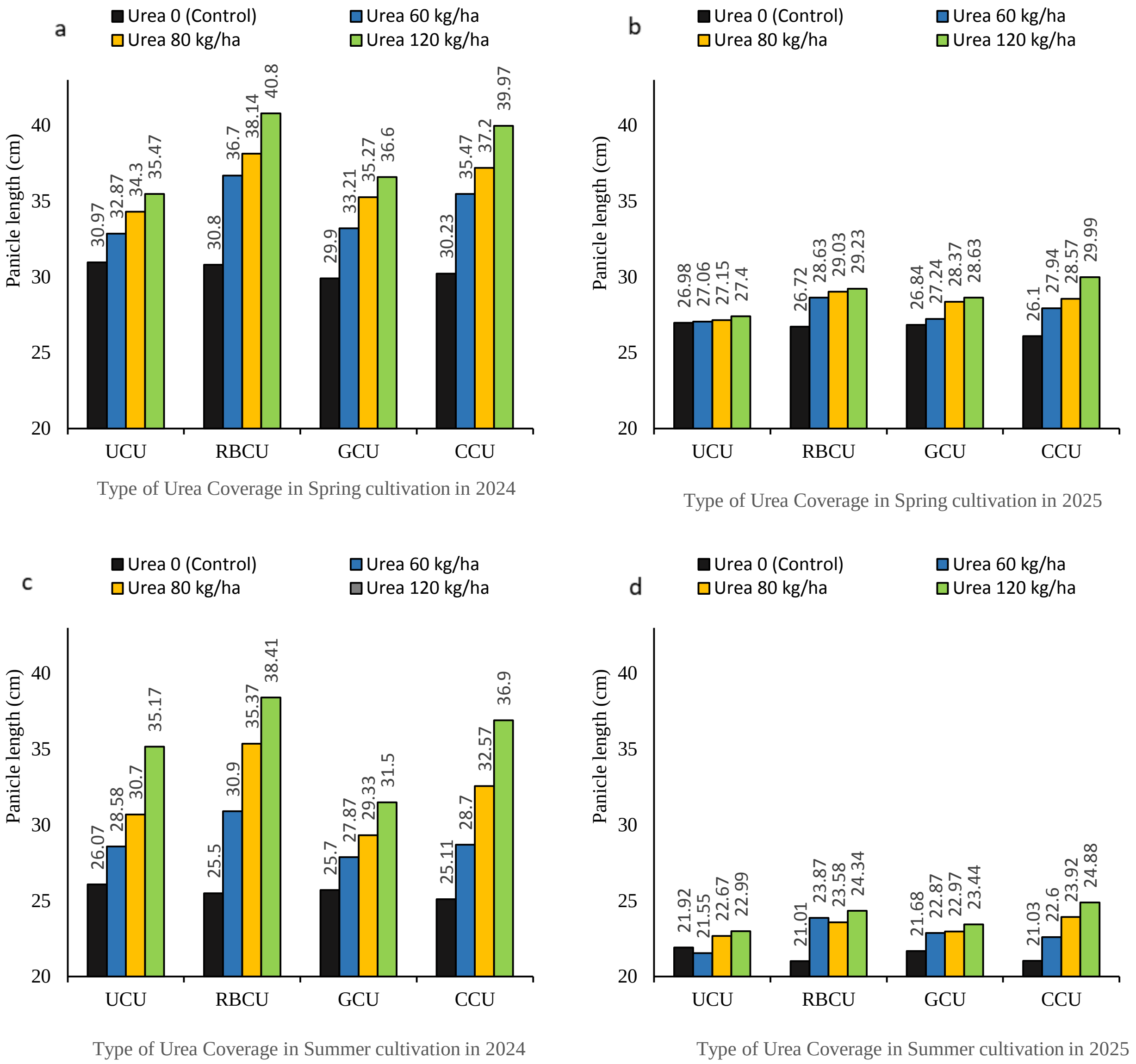

Figure 6. Interactive effects of year, planting season, urea coating type, and nitrogen rate on panicle length in proso millet. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 1.542.

Biomass and harvest index

Biomass and HI were significantly influenced by the four-way interaction among year, planting season, urea coating type, and nitrogen rate (Table 1). The physiological advantages conferred by RBCU translated into superior dry matter production and more efficient assimilate partitioning. Under summer heat stress, biomass production was severely reduced. However, RBCU at 80 kg urea ha^{-1} mitigated this reduction, producing 10.121 t ha^{-1} in summer 2024, which was 17.3% higher than the UCU control (8.630 t ha^{-1}) (Figure 7c). Under summer conditions in 2024, RBCU produced a higher HI than uncoated urea, indicating improved assimilate partitioning to the grain (Figure 8c). Although HI declined in the summer of 2024, improved HI values were observed in summer 2025 compared with spring 2025 (Figures 8b and 8d). In summer 2025, a season characterized by severe heat stress, the HI of the RBCU treatment at 80 kg urea ha-¹ (15.91%) was 6.3% higher than that of the UCU control at the same N rate (14.96%) (Figures 8b and 8d). These results indicate that RBCU maintained a higher HI under summer stress conditions.

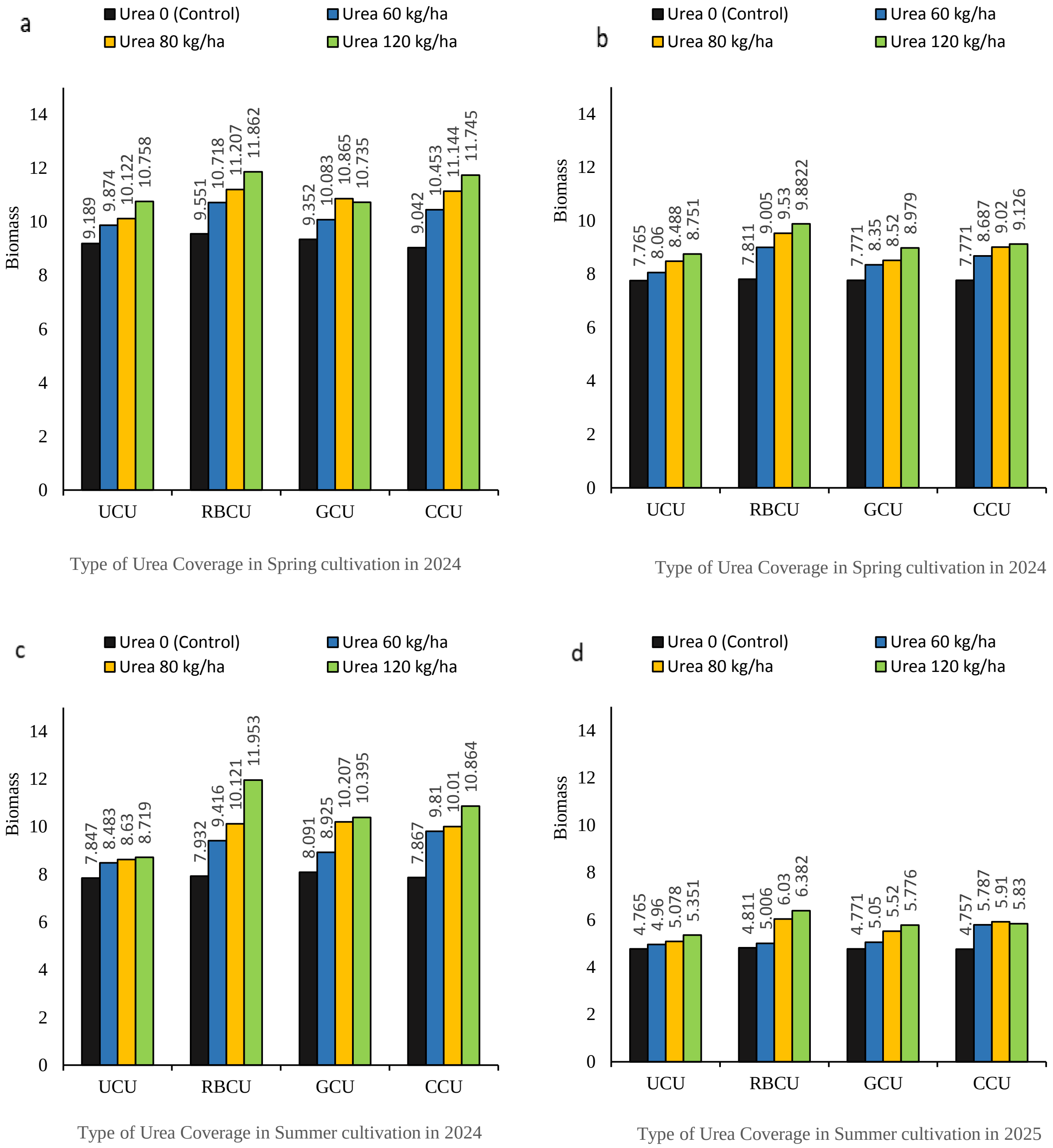

Figure 7. Interactive effects of year, planting season, urea coating type, and nitrogen rate on biomass in proso millet. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 0.794.

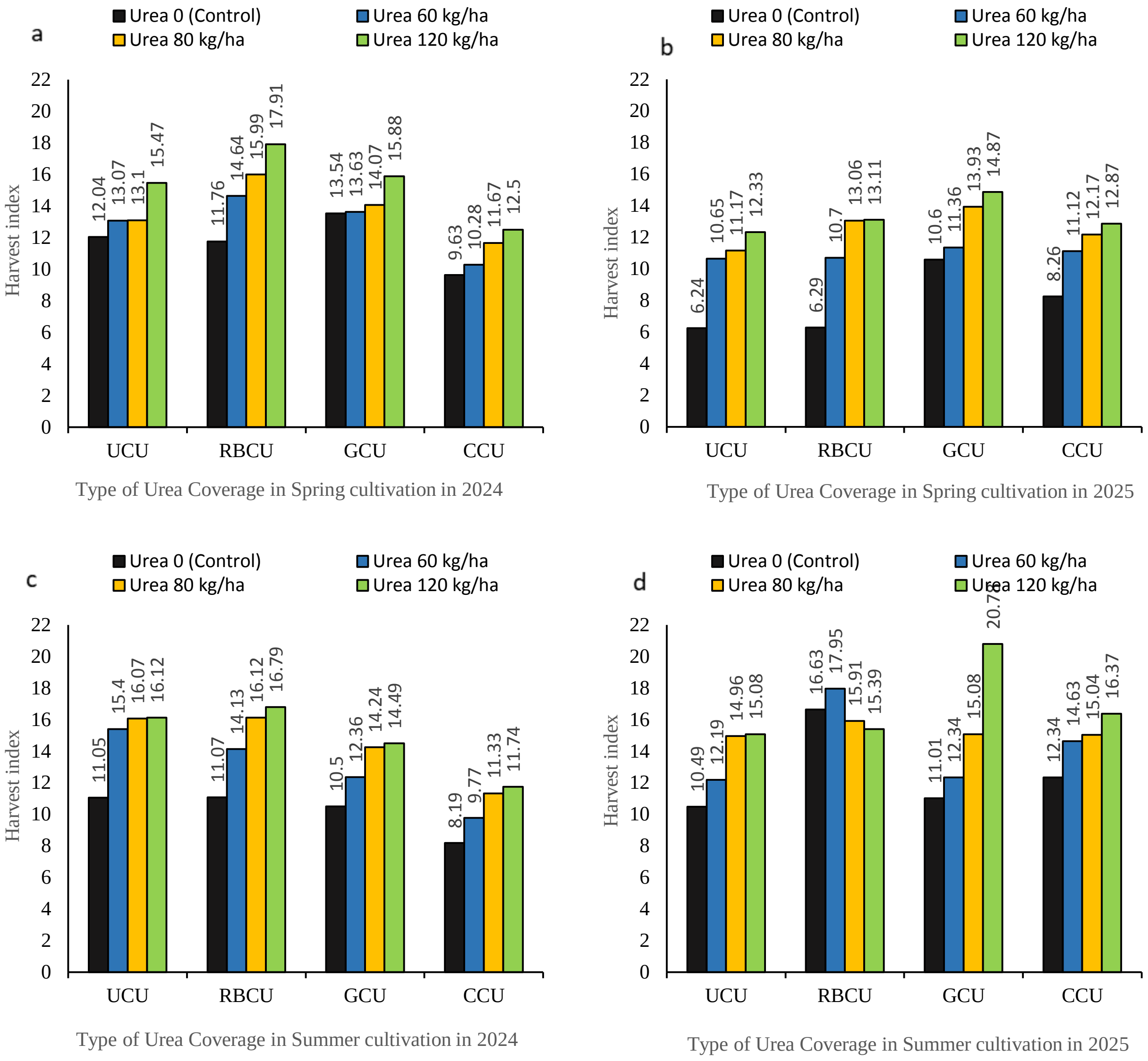

Figure 8. Interactive effects of year, planting season, urea coating type, and nitrogen rate on harvest index in proso millet. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 1.335.

Grain yield

Grain yield was significantly influenced by the four-way interaction among year, planting season, urea coating type, and nitrogen rate (Table 1). Heat stress generally reduced the grain yield of proso millet; however, urea coating mitigated the adverse effects of this stress (Figures 9c and 9d). Averaged across the two years, RBCU outperformed the other urea coating treatments and the control, especially at 80 and 120 kg urea ha^{-1} (Figures 9c and 9d). In summer 2024, grain yield reached 1.942 t ha^{-1} with RBCU at 80 kg urea ha^{-1}, compared with 1.653 t ha^{-1} for UCU at the same N rate, representing a 17.5% increase (Figure 9c). RBCU also produced higher grain yield in the spring season, averaged across the two years, compared with the other treatments (Figures 9a and 9b).

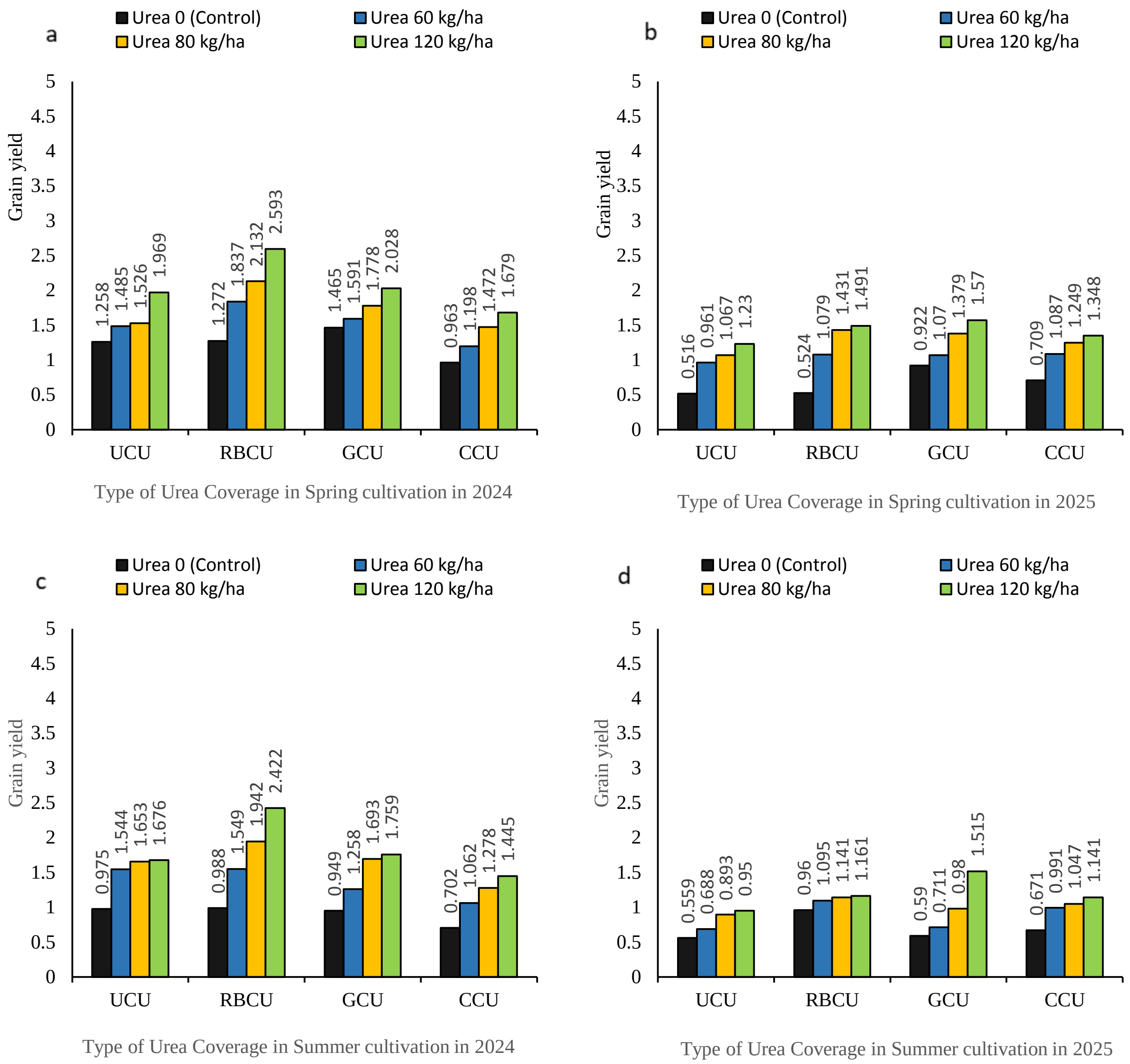

Figure 9. Interactive effects of year, planting season, urea coating type, and nitrogen rate on grain yield in proso millet. (a): Spring 2024, (b): Spring 2025, (c): Summer 2024, (d): Summer 2025; UCU: Uncoated urea (control), RBCU: Rice bran-coated urea, GCU: Gypsum-coated urea, CCU: Cement-coated urea; HSD5% = 0.249.

Discussion

Given the significant interaction among year, planting season, urea coating type, and nitrogen rate observed for all traits, except days to physiological maturity (Table 1), treatment effects varied across years and seasons; therefore, interpretations were dependent on the environmental context. Our study demonstrated that RBCU improved physiological performance under summer heat conditions, as reflected by higher pigment retention, moderated phenology, and maintained biomass partitioning. These findings align with the broader concept that improving nitrogen use efficiency is central to sustainable crop production (Dobermann 2007; Hawkesford 2014; Hawkesford *et al.* 2021), particularly under abiotic stress conditions.

A significant preservation of chlorophyll *a* (25.4% higher) and carotenoids (93.6% higher) was observed under RBCU compared with the control (UCU) at 80 kg urea ha^{-1} under summer heat stress (Figures 3c and 4c). In addition to their role in light harvesting, carotenoids act as critical antioxidants that protect the photosynthetic apparatus from photo-oxidative damage exacerbated by heat stress (Ashraf and Harris 2013). The sustained nitrogen availability provided by RBCU may have supported continued pigment synthesis under stress conditions, thereby maintaining source activity during periods that would otherwise lead to irreversible degradation, a common response in plants exposed to drought (Sarvari *et al.* 2017). Concurrently, the improved leaf area and panicle length indicate that RBCU supported greater canopy development and sink capacity. This finding agrees with the principle that maintaining canopy integrity and photosynthetic structure under stress is crucial for sustaining yield potential, as demonstrated previously in wheat under drought conditions (Askary *et al.* 2018). The physiological basis for this preservation likely stems from the steady nitrogen supply, which prevents the resource deprivation that typically accelerates senescence under stress. Enhanced leaf area and panicle length under controlled nitrogen release contributed to improved light interception and sink capacity, both of which are essential for sustaining yield formation under stress conditions, as emphasized in previous studies (Reynolds *et al.* 2010).

Summer heat stress accelerated phenological development in proso millet. Accelerated phenology under summer planting represents a common heat-avoidance response; however, this response often limits biomass accumulation and yield potential (Sadras and Richards 2014). Nevertheless, RBCU mitigated this effect by delaying phenological development. The delayed heading observed under RBCU suggests that nitrogen synchronization influenced developmental timing under summer heat stress. Such phenological adjustment may contribute to improved performance under high temperatures. Similar fine-tuning of growth and development in response to the interaction between nitrogen and water supply has been reported as a key mechanism for yield stability in wheat (Cossani and Sadras 2018). Our findings suggest that coated urea may induce a similar adaptive response under heat stress conditions.

Although HI decreased in the summer planting of 2024 under RBCU treatment, it increased (6.3%) in the more stressful summer of 2025 compared with the control (Figure 8). This improved HI suggests that synchronization between nitrogen availability and crop demand plays a key role in maintaining assimilate partitioning efficiency under high-temperature conditions. Under stress, the sustained nitrogen availability provided by RBCU may support continued nutrient and assimilate flow to developing kernels, thereby reducing constraints on grain filling, which is a common cause of yield loss under heat stress. This finding is consistent with previous results in wheat, where optimized nitrogen application improved the remobilization of stem reserves to grains under terminal drought conditions (Ghahramani *et al.* 2018). More broadly, these findings highlight that enhancing nitrogen use efficiency involves not only improved uptake but also improved internal utilization and assimilate partitioning (Dobermann 2007). These results support the concept that yield stability under heat stress is driven primarily by developmental plasticity and resource allocation rather than solely by direct biochemical protection mechanisms (Blum 2011). Our findings, together with those reported for quinoa under combined drought and nitrogen stress (VaziriMehr *et al.* 2024) and maize under controlled-release urea application (Chen *et al.* 2020; Guo *et al.* 2020), indicate the benefits of synchronized nutrient release in regulating growth dynamics and biomass allocation patterns under stress conditions.

We propose that RBCU at 80 kg N ha^{-1} coordinates multiple physiological processes: sustaining the photosynthetic source, moderating developmental timing to reduce stress risk, and improving assimilate translocation to the grain sink. This coordinated response may explain the observed yield advantage under summer heat conditions. These findings highlight the potential of controlled nitrogen release as a management strategy for improving yield stability under heat stress.

Conclusion

This study demonstrated that RBCU was associated with improvements in several physiological and yield-related traits under heat stress conditions, including the following:

- Modulation of crop phenology by delaying heading and maturity, therby extending the vegetative and grain filling periods, which may contribute to improved performance under high temperatures.
- Preservation of photosynthetic integrity through maintaining higher levels of chlorophyll a and protective carotenoids, which are crucial for sustained assimilate production under heat.
- Optimization of canopy architecture by supporting greater leaf area and panicle development, thereby enhancing light interception capacity and sink size.
- Enhancement of biomass partitioning efficiency through increased HI, ensuring that a greater proportion of total dry matter is allocated to grain production under stress conditions. Consequently, RBCU at 80 kg urea ha^{-1} was associated with improved physiological stability and grain yield under summer heat conditions. Controlled nitrogen release supported

sustained crop growth under elevated temperatures and significantly improved grain yield compared with conventional urea.

This study, together with related research on nutrient-stress interactions in other crops, contributes to a broader understanding of the role of nitrogen management under heat stress conditions. The results suggest that RBCU may represent a promising nitrogen management strategy for heat-prone environments.

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Author Contribution

Shrooq Abbas conducted the experiment and wrote the manuscript with support from Sirous Hassannejad. Sirous Hassannejad supervised the project. Soheila Poorheidar Ghafarbi assisted with project supervision. All authors discussed the results and contributed to the final version of the manuscript.

Conflict of Interest

The authors declare that they have no competing interests related to the subject of this article.

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